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Multisatellite Constellation Configuration Selection for Multiregional Highly Elliptical Orbit Constellations

Mark G. Matossian

University of Colorado, Colorado Center for Astrodynamics Research
Boulder, Colorado 80309-0431

ABSTRACT

The Archimedes Project is a joint effort of the European Space Agency (ESA) and the National Space Development Agency of Japan (NASDA). The primary goal of the Archimedes project is to perform a technical feasibility analysis and preliminary design of a highly inclined multisatellite constellation for direct broadcast and mobile communications services for Europe, Japan and much of North America. This report addresses one aspect of this project, specifically an analysis of continuous satellite coverage using multiregional highly elliptical orbits (M-HEOs). The analysis methodology and ensuing software tool, named SPIFF, were developed specifically for this project by the author during the summer of 1992 under the STA/NSF Summer Institute in Japan Program at Tsukuba Space Center.

2.0 INTRODUCTION: THE ARCHIMEDES PROJECT

2.1 Archimedes and 1992 World Administrative Radio Conference

The Archimedes project is an outgrowth of the 1992 World Administrative Radio Conference (WARC-92) that allocated worldwide frequency bands for a variety of services to be phased in over a period of years. Included in these bandwidth assignments were allotments for direct satellite radio broadcasting (DBS-R), mobile communications, navigation and other services. With the significant progress in clarifying bandwidth use from WARC-92, the Archimedes project was initiated to investigate the technical aspects of providing DBS-R services.

2.2 Coverage areas and elevation angle

Archimedes originally began at ESA with examination of highly elliptical Molniya (12 hr. period) and Tundra (24 hr. period) orbits for European coverage. The program has now expanded to include other non-geosynchronous orbits such as M-HEOs to serve several markets, and the participation of NASDA.

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Satellite services now under consideration include DBS-R, mobile communications, navigation and possibly meteorological services. The coverage areas have expanded to include Japan, most of the contiguous US, and the US/Canada border area. (90% of the Canadian population is located within a few hundred kilometers of the US border.) This multi-regional scenario reduces user costs by expanding market opportunities and improving economies of scale. Analysis was done for both 30° and 40° elevation angle continuous satellite coverage in each coverage zone.

2.3 Multiregional-highly elliptical orbit constellations

The goal of this analysis was to determine the configurations of multi-satellite HEO constellations capable of providing continuous coverage to the European, Japan and North American coverage zones mentioned above. Typically, a constellation consisted of P orbital planes of Q satellites/plane for a total of $N=P*Q$ satellites. Furthermore, a harmonic phase distribution factor, M , is necessary to describe the initial distribution of the satellites within a plane and in relation to the neighboring planes. The harmonic factor is discussed in greater detail in the Multisatellite Constellation Analysis section below.

In each orbital plane, a highly elliptical orbit with a low perigee was selected (altitude=1000 km.) to keep the energy of the orbit relatively low but with sufficient altitude to largely avoid drag effects. The argument of perigee was selected to be 270° to place the satellite at apogee over the Northern Hemisphere coverage areas. Likewise, an inclination of 63.4° is necessary to avoid precession of the argument of perigee. The selection of the longitude of the ascending node for each orbital plane was selected so that each plane was equally separated from neighboring planes ($360°/P$). This assured that apogee for at least one of the planes would be centered over a coverage area, in this case Europe. Periods of 3, 4, 6 and 8 hours (even factors of 24 hours) were examined so that the ground track would repeat. Low apogee 3 and 4 hour period orbits were quickly determined to require too many satellites and the analysis focused on 6 and 8 hour orbits. The selection of the period then enabled the radius of apogee and the eccentricity to be determined.

3.0 MULTISATELLITE CONSTELLATION ANALYSIS STRATEGY

3.1 Introduction

Constellation analysis has been conducted at least as far back as 1961 in the area of continuous zonal coverage.¹ In the 1970's, John Walker² and G. V. Mozhaev³ developed innovative algorithms for continuous global coverage. In

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1980⁴, the late Arthur Ballard extended and generalized the work of Walker for the U.S. NAVSTAR/GPS program.

For the Archimedes analysis it was helpful to use elements of Ballard's analytical approach, however improvements and corrections to Ballard's work was necessary. Still, significant differences remained, such as the employment of elliptical trajectories and discrete zonal coverage, that required the development of a new algorithm. Nonetheless, credit is due to Walker, Ballard, et al. for inspiration in the modeling strategy employed for this study that is embedded in the SPIFF software.

3.2 Coordinate systems

SPIFF works in an Earth-Centered Earth-Fixed (ECEF) coordinate system. The published algorithms mentioned above use an Earth-Centered Inertial (ECI) coordinate system since their goal is global Earth coverage - independent of points fixed on the Earth's surface. The requirement for discrete zonal coverage resulted in the use of an ECEF system. Essentially, the Earth is held fixed and the entire constellation is rotated around it through manipulation of the longitudes of the ascending nodes of the orbital planes.

As a result, SPIFF is a coverage zone based algorithm. Satellite coverage analysis is often based on what a specific satellite can "see", however the driving requirement for Archimedes was actually that coverage areas had line of sight visibility of any satellite at greater than a user-specified elevation angle. This results in a subtle difference in the question that the algorithm answers. Instead of asking whether the satellites have line-of-sight to all parts of each of the coverage zones, the question is reversed to, "Can anyone, anywhere in the coverage zone, always have line of sight to at least one satellite at greater than a <user specified> elevation angle?" Thus SPIFF drives the simulation from the users' perspective.

3.3 An overview of the sequence of calculations

After the usual initialization procedures, SPIFF reads in the user's specifications for the run from a data file. In addition to specifying limits for P, Q and N, the user may assign several variables that control the resolution of the analysis, orbital periods to be considered, the coverage areas, and the minimum elevation angle therein. Next the program performs some preparatory calculations on the geometry of the coverage areas and the some of the orbital elements of the constellations to be considered.

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SPIFF now enters into a series of nested loops to test all the possible orbits as specified by the user. After P and Q have been specified, a loop for the harmonic factor, m, is entered and the candidate constellation is calculated.

Once the constellation has been determined, a nested ascending node offset loop is entered to test for the different constellation ECEF positions in terms of longitude of the ascending node. Recall that the orbit is repetitive since the periods are factors of 24 hours and the small J2 effect on precession of the ascending node for a highly elliptical orbit may be accommodated through a slight period adjustment in the orbit.

Now a 24 hour time propagation loop is begun. the satellites are assigned their longitude of ascending node according to their initial distribution, the ascending node offset, and Earth rotation. This converts the orbital elements, an ECI-based system, to ECEF coordinates since the orbital elements interface with the inertial and fixed coordinate systems through the ascending node. Note that the right ascension of the ascending node is an ECI term fixed to the former position of the First Point in Aries, whereas the longitude of the ascending node is an ECEF argument. Time zero corresponds to vernal equinox when the two coordinate systems' axes are collinear.

The phase distribution can also now be determined. One of the modifications from Ballard's and Walker's work is that their phase distribution for circular orbits must be converted to true anomaly of an elliptical orbit. This can be accomplished several ways and SPIFF uses the phase distribution for a circular orbit as a percentage of the period (adjusted for 360 degrees). The resulting time separation value is first converted to mean anomaly through a recursive method and then to true anomaly.

Finally, SPIFF enters another nested loop for checking the coverage of each zone. First there is a check for single satellite coverage of the entire zone. Failing that, there is a check for multisatellite coverage. To check for multisatellite coverage, points on the circumference of the circular coverage zone and the center of the zone are checked for elevation angles to satellites in view.

Full coverage for 24 hours assures that the constellation will have continuous coverage. This is because the selected periods repeat at least once every 24 hours and the ascending node precession is neutralized through orbital maneuvers.

3.4 Constellation harmonics

As mentioned above, the SPIFF code cycles through a user specified range for P and Q. However, within the designation of a constellation of P planes and Q satellites/plane, there can be many permutations. Ballard introduced a

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harmonic factor M that is used as a multiplier with the right ascension to derive the initial phase angle of a circular orbiting satellite.⁵ The longitude of the ascending node at time=0 and the time separation of the satellites can then be derived. It is very important at this stage to check against duplication of constellation configurations derived from different M values as the Ballard algorithm, though compact, is rife with duplication resulting in excessive run times. The algorithm in SPIFF was modified to eliminate duplicated permutations. The user may specify a range for P & Q , a step size for each, and a maximum number of satellites to be considered in a candidate constellation.

3.5 Coverage zone definition

The three coverage areas are represented in the SPIFF program by four circular coverage zones shown below in figure 3.5.1.

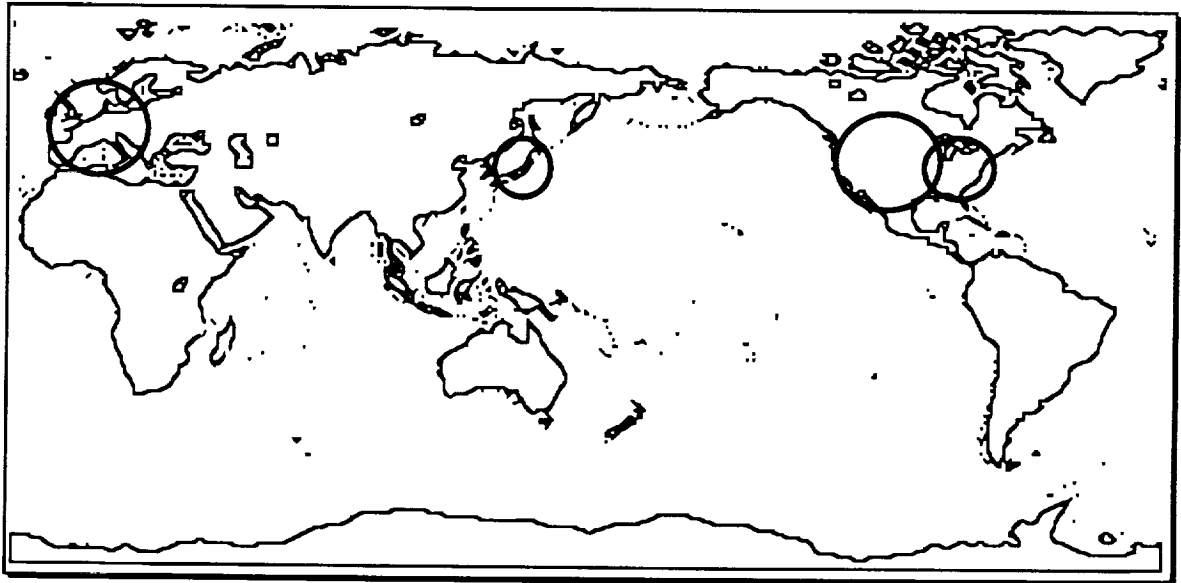


Figure 3.5.1 Circular coverage zones

The circular coverage zones may be easily described by a vector and an angle arc: the vector from the center of the Earth to the center of the coverage circle on the surface of the Earth fixes the location of the coverage zone; and the arc on the surface of the Earth from the center of the circle to the circumference of the circle. Please refer to figure 3.5.2.

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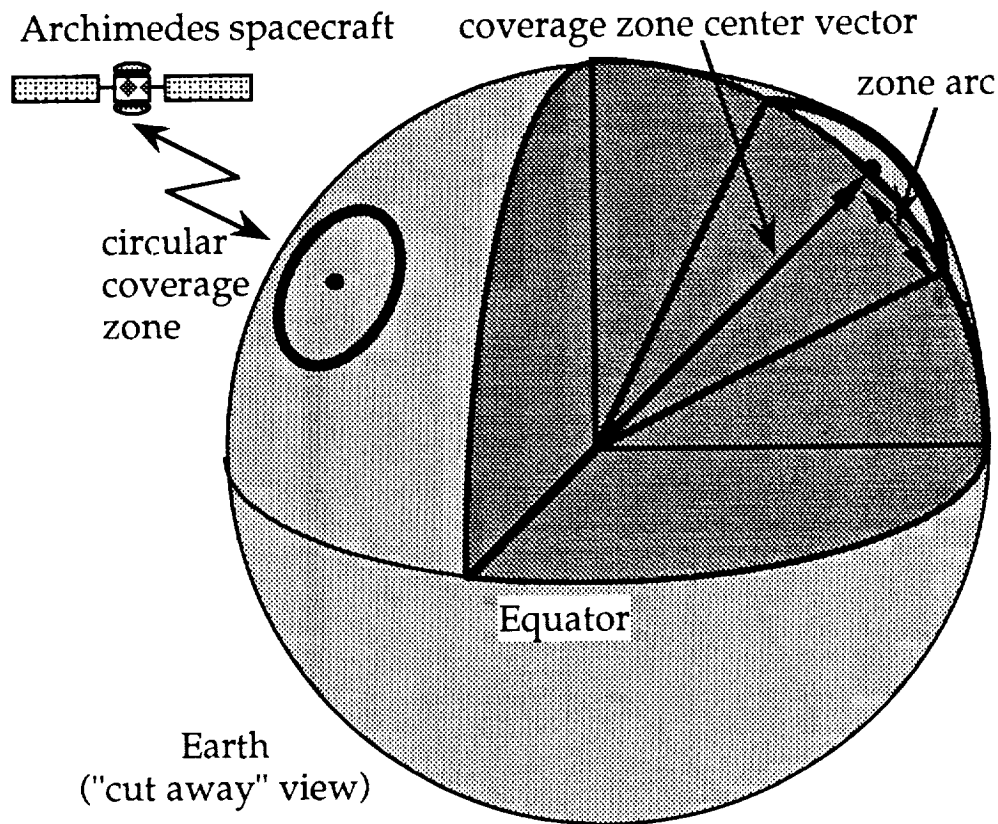


Figure 3.5.2 Coverage zone cross section

3.6 Coverage check

Checking for single or multisatellite coverage is accomplished by simple vector manipulation. For a point on the surface of the Earth to have proper satellite coverage, the satellite must be in a cone extending outward from the Earth from that point and at an angle with the tangential plane equal to the minimum elevation angle. Please refer to figure 3.6.1. For full zonal coverage by a single satellite, the satellite must be located within a cone that is the locus of all the coverage cones from the circumference of the circular zone. In the event that single satellite coverage is not possible, multisatellite coverage of a zone is checked by assuring that individual coverage cones on the circumference of the circle, as well as the circle center, each contain a satellite.

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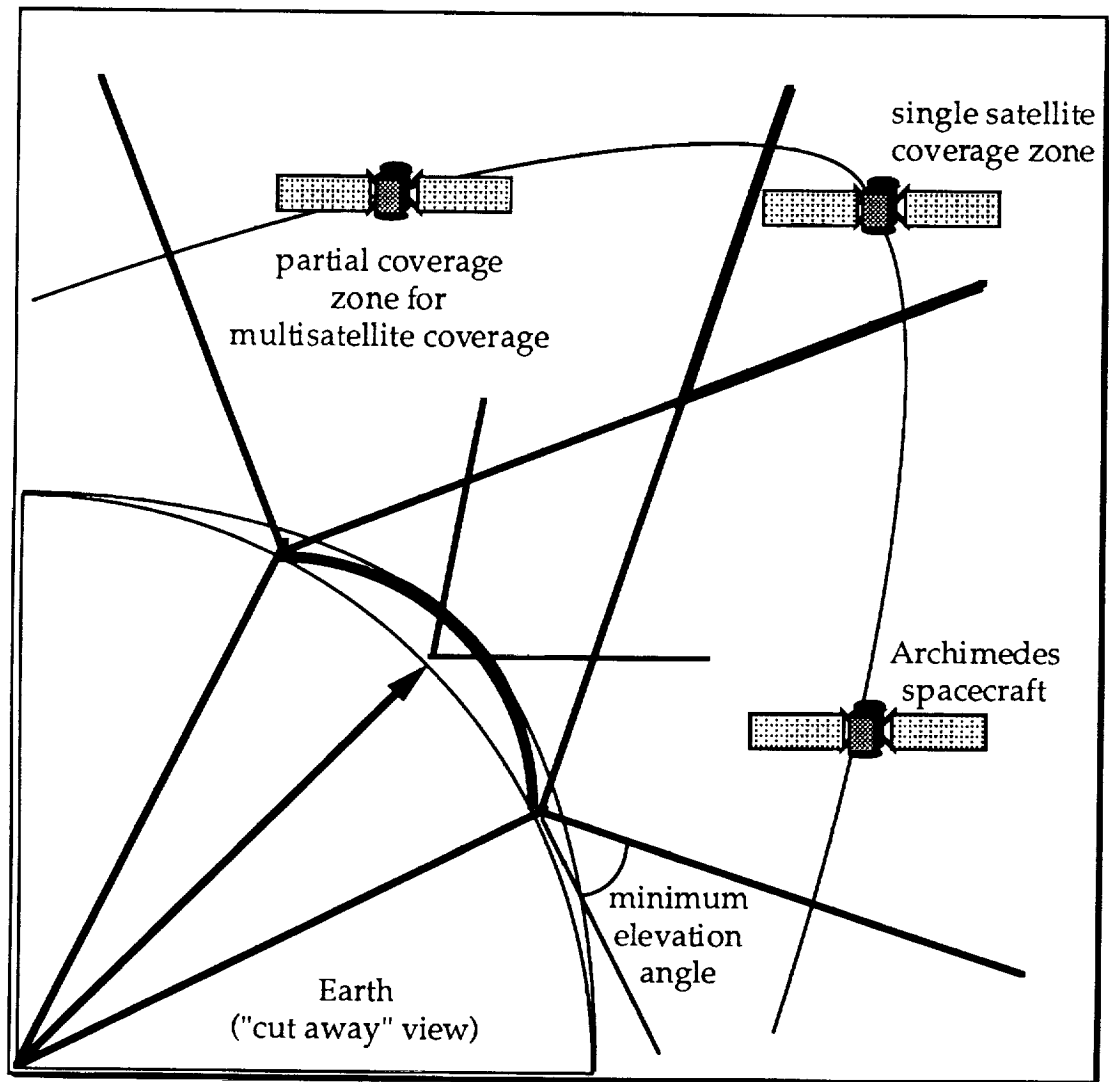


Figure 3.6.1 Full and partial coverage cones

4.0 RESULTS

4.1 Data

Several runs of the SPIFF program were made under specific conditions to test for candidate Archimedes systems. Constellations of up to $P=6$ planes and maximum value of $N=P*Q=10$ was specified. The zones were specified as shown in table 4.1.1.

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Table 4.1.1 Coverage zones' centers and arc lengths (degrees)

	Europe	Japan	W. US/CAN	E. US/CAN
Longitude	10	138	253	278
Latitude	50	38	40	40
Arc length	15	11	17	12

The minimum elevation angles considered were 30 and 40 degrees, and the orbit was tested for 6 and 8 hour periods for different runs. These results can be seen in tables 4.1.2 and 4.1.3.

Table 4.1.2 40° elevation angle results

Elev. Angle	Period	P	Q	N	M
40°	6 hr.	-	-	-	-
40	8	5	2	10	4.5
40	8	6	1	6	3.0

At the stringent conditions (40 degree minimum elevation angle and 6 hr. period), there were no constellations that could provide continuous coverage. However, there were two constellations in 8 hour orbits capable of providing continuous coverage: a 10 satellite constellation of 5/2/4.5 (P/Q/M) and another requiring only 6 satellites in a 6/1/3 configuration.

Table 4.1.3 30° elevation angle results

Elev. Angle	Period	P	Q	N	M
30°	6 hr.	5	2	10	4.5
30	8	5	1	5	2.0
30	8	5	2	10	2.5
30	8	5	2	10	4.5
30	8	6	1	6	3.0

When the minimum elevation angle requirement is opened up to 30 degrees, it is revealed that there is a 6 hour period constellation that could provide continuous coverage with 5 planes of 2 satellites/plane. In the 8 hour period case, we see that there are several acceptable constellations.

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4.2 CONCLUSIONS

The number of planes (P), the number of satellites (N), and the line-of-site elevation angle are important criteria for rating constellations. High values of P and N are undesirable due to operational complexity and cost.

Elevation angle is an important consideration for communications due to signal interference. In order to successfully communicate at lower elevation angles, the power density flux of a signal from a satellite must be stronger. The achievement of high power level transmissions typically results in higher spacecraft weights and is undesirable, hence the emphasis on high minimum elevation angles for communications.

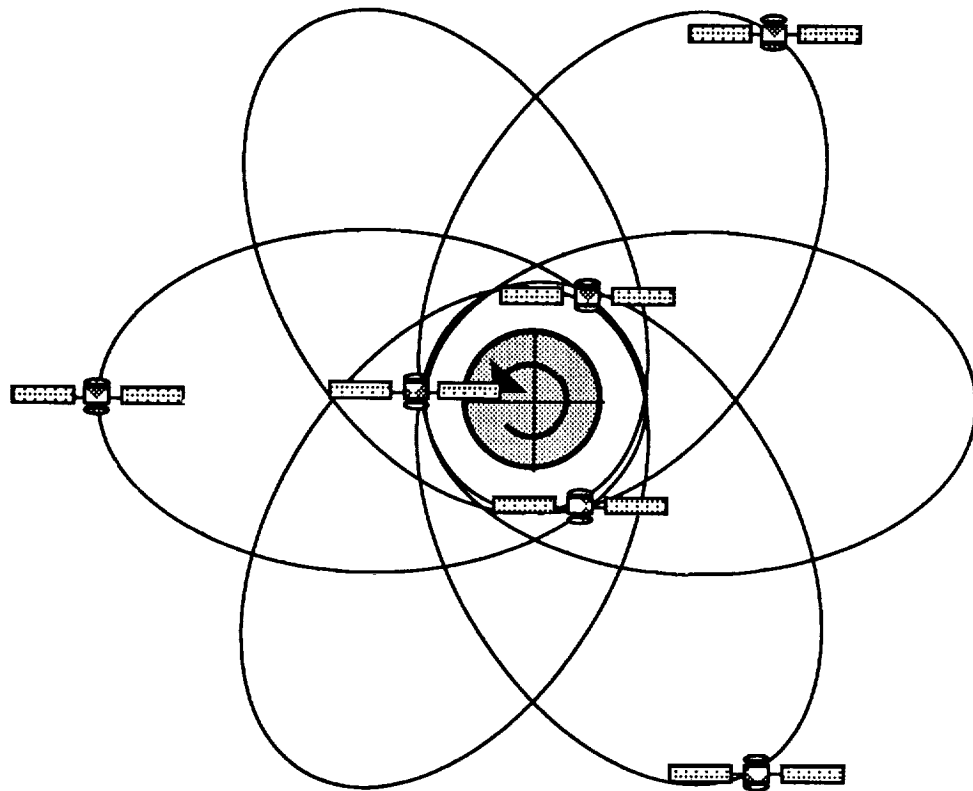


Figure 4.2.1 A constellation option that satisfies the 40° elevation angle & 8 hour period constraints with a $P=6/Q=1/M=3$ configuration (polar view).

The 8 hour/40 degree elevation angle results show that it is possible to achieve relatively high elevation angles. The balance between having fewer satellites as an initial cost in the 6/1/3 case vs. 5/2/4.5 must be weighed against the additional operational costs of having more planes.

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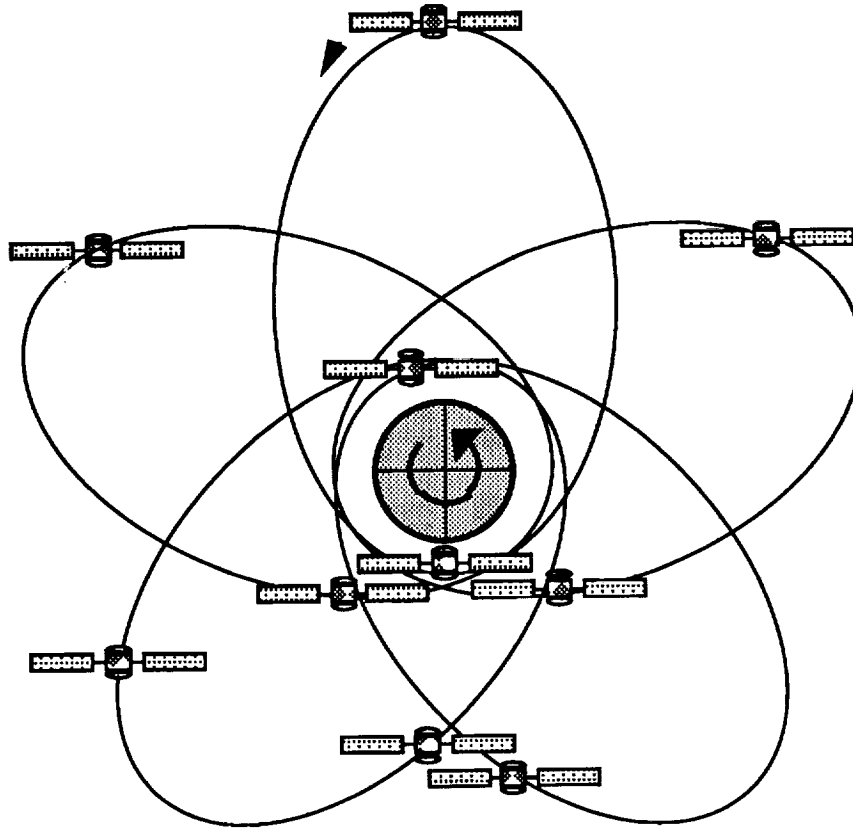


Figure 4.2.2 A second constellation option that satisfies the 40° elevation angle & 8 hour period constraints with a $P=5/Q=2/M=4.5$ configuration (polar view).

At lower elevation angles, the 6 hour period is attractive for its shorter time delay in communication due to its lower apogee, but will have larger J2 effects to expend propellant counteracting and thus shortening its operational lifetime. The 8 hour case reveals an interesting result that there is a 5/1/5 solution with both a low number of planes and a low total number of satellites. This would be an especially attractive configuration if the low minimum elevation angle results in acceptable power flux density requirements on the spacecraft design.

It should be noted that these results conflict with those previously published in the ESA Bulletin⁶ by Solari and Viola. These differences need to be reconciled. I was, however, able to duplicate their results in the course of developing an independent program for checking the coverage zone satellite hand-off that neglected Earth rotation. When Earth rotation was added to this program, the results matched those of SPIFF.

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5.0 ACKNOWLEDGEMENTS

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